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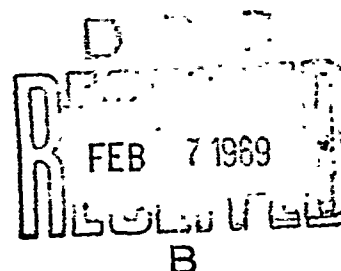
AD847319

Precision Measurement of Satellite Acceleration The LOGACS Experiment

Prepared by B. L. ADAMS, E. G. FOTOU, and E. LEVIN
Electronics Division

68 JUL 15

Engineering Science Operations
AEROSPACE CORPORATION



Prepared for SPACE AND MISSILE SYSTEMS ORGANIZATION
AIR FORCE SYSTEMS COMMAND
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Los Angeles, California

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Air Force Report No.
SAMSO TR 69-6

Aerospace Report No.
TR-0200(4306-02)-5

PRECISION MEASUREMENT OF SATELLITE ACCELERATION:
THE LOGACS EXPERIMENT

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Engineering Science Operations
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FOREWORD

This report is published by the Aerospace Corporation, El Segundo, California, under Air Force Contract No. F04701-68-C-0200.

This report, which documents research carried out from May 1966 to October 1967, was submitted on 3 May 1968 to Lt. Colonel M. Michael Bonner, SMGS, for review and approval.

Permission to use the photographs designated as "Fig. 4," "Fig. 5," "Fig. 6," and "Fig. 8" was granted by Bell Aerosystems Company, Buffalo, New York. Permission to use the photographs designated "Fig. 11" and "Fig. 12" was granted by Lockheed Missiles and Space Company, Sunnyvale, California.

Approved


D. R. S. McColl, General Manager
Electronics Division

Publication of this report does not constitute Air Force approval of the report's findings or conclusions. It is published only for the exchange and stimulation of ideas.


M. MICHAEL BONNER
Lt Colonel, USAF

ABSTRACT

In May of 1967 an extremely sensitive accelerometer was flown in satellite orbit and successfully gathered approximately 100 hr of precise deceleration data. A unique feature of the experiment was the accurate calibration of the accelerometer in the orbital environment at a level commensurate with the very low non-conservative forces to be sensed. The experiment was designated LOGACS (LOW-G Accelerometer Calibration System).

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SECTION I

INTRODUCTION

Accurate and continuous measurements of the acceleration of a satellite vehicle may be used to infer atmospheric density variations and may have potential application to improve satellite navigation and orbit prediction. The forces involved are extremely small, and although accelerometers capable of sensing such levels exist, their calibration prior to launch can only be accomplished in the 1-g earth environment. This is so different from the ambient environment on-orbit that the calibration cannot be reliably extrapolated. Second order couplings and minor effects which are negligible under 1-g conditions become significant and interact in a manner which complicates the extrapolation process. It should be emphasized that such phenomena become important only if extreme precision is desired. They generally can be ignored if a relatively coarse measurement accuracy is adequate.

The accurate calibration of an accelerometer which was sensitive enough to measure the very low non-conservative forces in the orbital environment was achieved in an experiment designated LOGACS (LOW-G Accelerometer Calibration System). The experiment was flown in satellite orbit in May of 1967 and successfully gathered approximately 100 hr of precise deceleration data. This report presents a description of the LOGACS experiment and the technique used to calibrate the extremely sensitive accelerometer used in the experiment. For comparison, three other satellites (San Marco, SPADES, and Cannonball) which infer atmospheric density by sensed deceleration are described in Appendix A. Two of these, SPADES and Cannonball, use the same accelerometer as LOGACS, but since the primary purpose of these satellites is atmospheric research, they do not utilize the calibration techniques employed in the LOGACS experiment to achieve the high precision required as a basis for accurate space navigation.

SECTION II

CALIBRATION PLAN

The output of an accelerometer may be represented to first order by

$$A = K(B + A_s) \quad (1)$$

where

A = accelerometer output

K = scale factor

B = bias

A_s = sensed acceleration

Calibration consists of determining the scale factor K and bias B . Ideally these quantities remain constant; however, it is well known that they vary with changed environmental conditions and may vary with time. Hence periodic recalibration is required.

The technique employed by LOGACS utilizes a turntable with the accelerometer mounted so that the center of mass of the sensitive element is a known distance R from the center of rotation and the turntable acts as a centrifuge with a known angular velocity ω . The arrangement is shown schematically in Fig. 1. The rotation generates a centripetal acceleration of magnitude $R\omega^2$ which serves as the standard for calibration purposes. The values actually used in the flight were $R = 3.97$ in. and $\omega = 0.44495$ rpm. The accelerometer output now becomes

$$A = K(B + A_{\text{drag}} \cos \omega t + R\omega^2) \quad (2)$$

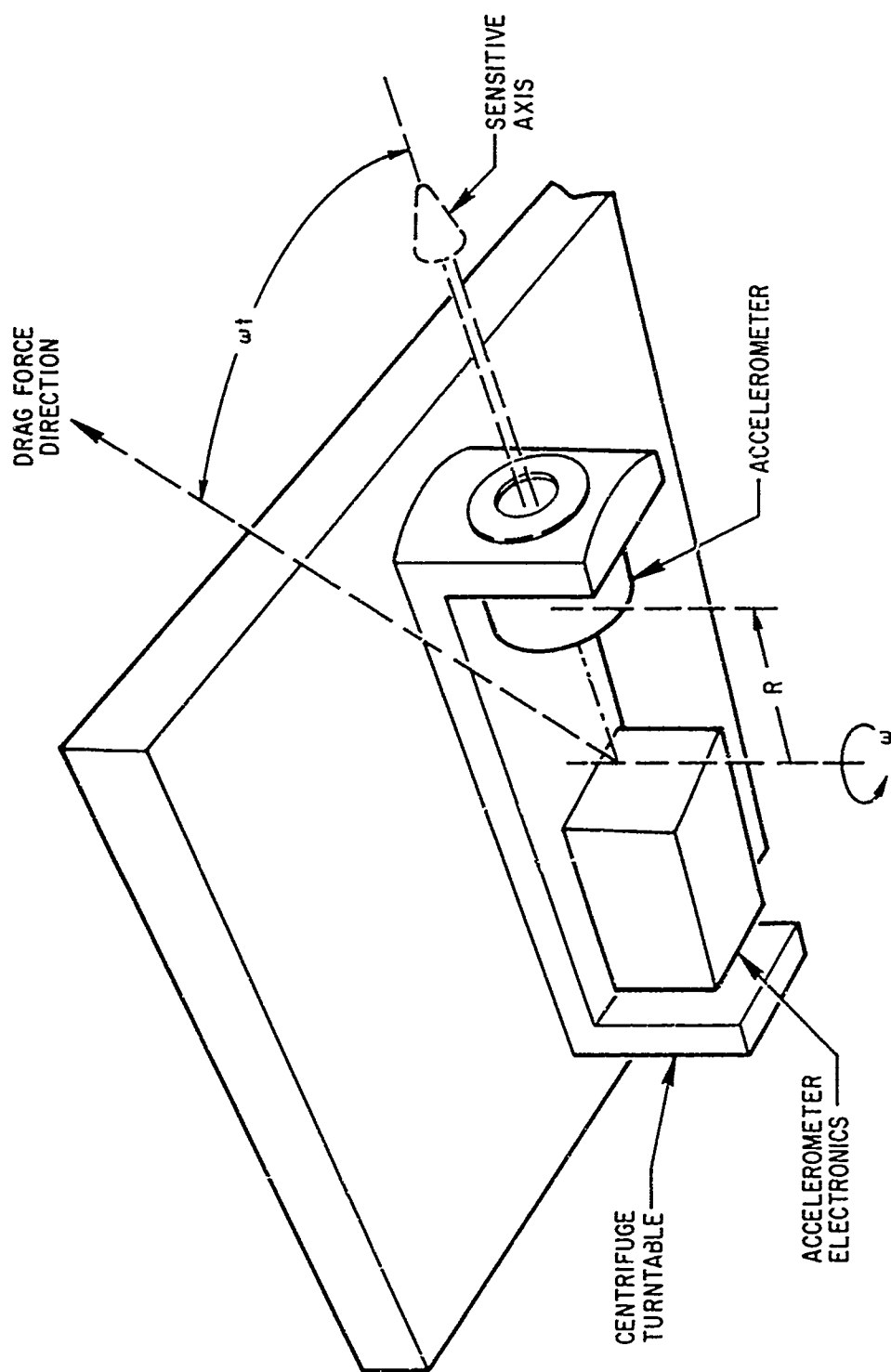


Figure 1. Arrangement of LOGACS Calibration Centrifuge

The turntable actually was designed to operate in four modes with corresponding output as shown in Table 1. These four modes were programmed to follow one another in sequence, each lasting 512 sec. The expected form of the output over a full cycle is shown in Fig. 2 (for a hypothetical case of constant drag).

Table 1. Turntable Modes

<u>Mode</u>	<u>Description</u>	<u>Accelerometer Output</u>
1	Rotation at fixed angular speed ω	$A_1 = K(B + A_{\text{drag}} \cos \omega t + R\omega^2)$
2	Rotation at fixed angular speed 2ω	$A_2 = K(B + A_{\text{drag}} \cos 2\omega t + 4R\omega^2)$
3	No rotation ($\omega = 0$), sensitive axis forward	$A_3 = K(B + A_{\text{drag}})$
4	No rotation ($\omega = 0$), sensitive axis aft	$A_4 = K(B - A_{\text{drag}})$

In order to illustrate how these modes permit the determination of bias B and scale factor K , imagine first the simplified case where drag remains constant during the calibration cycle. Then, the data from modes 3 and 4 can be combined to give

$$B = \frac{A_3 + A_4}{2K} \quad (3)$$

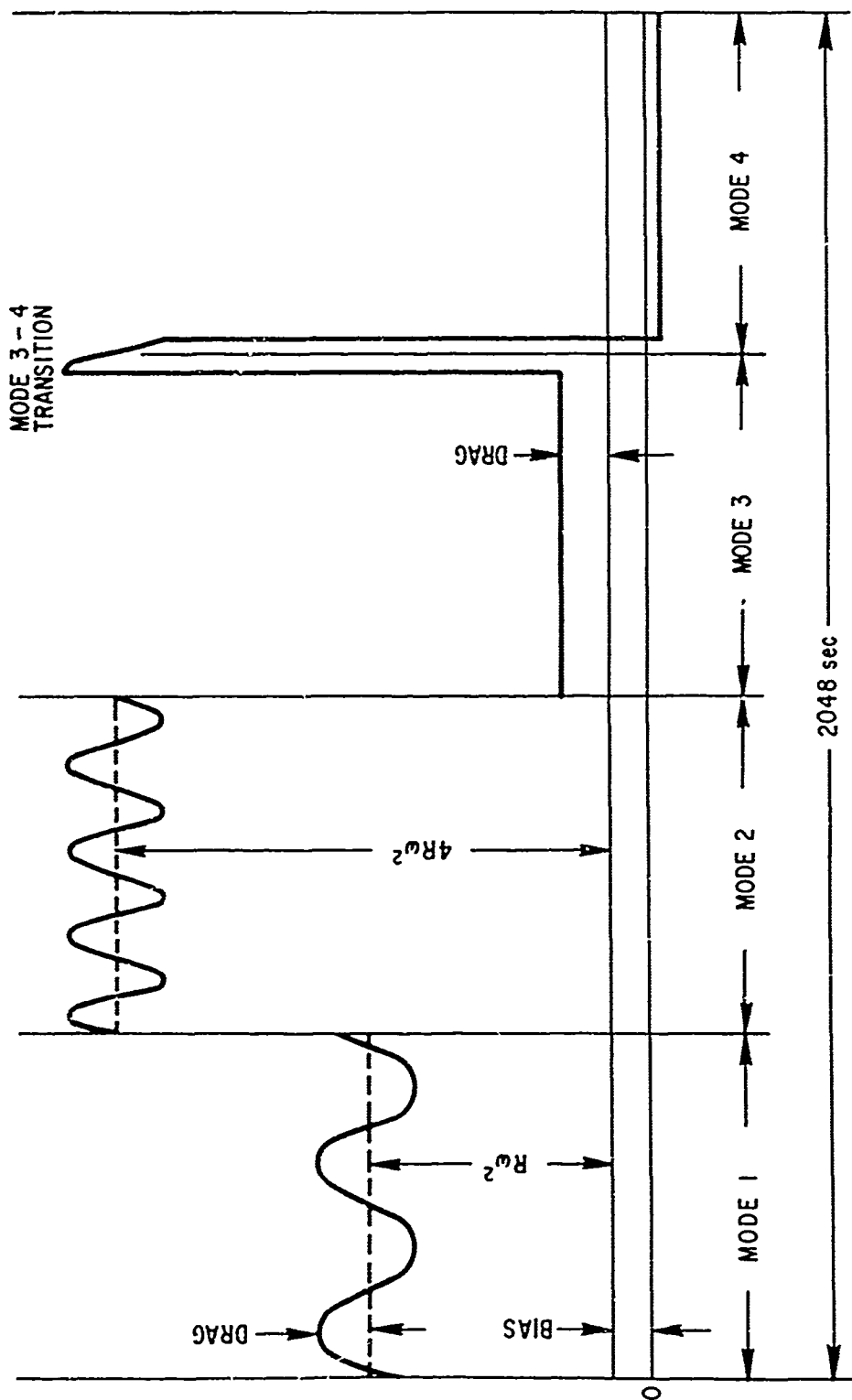


Figure 2. Characteristic Accelerometer Output (Constant Drag Case)

which would determine the bias once the scale factor is known. In modes 1 and 2, the accelerometer output may be integrated over one revolution of the centrifuge to yield

$$\bar{A}_1 \equiv \frac{1}{2\pi} \int_0^{2\pi} A_1 d\theta = K[B + R\omega^2] \quad (4)$$

$$\bar{A}_2 \equiv \frac{1}{2\pi} \int_0^{2\pi} A_2 d\theta = K[B + 4R\omega^2] \quad (5)$$

Then the scale factor becomes

$$K = \frac{\bar{A}_2 - \bar{A}_1}{3R\omega^2} \quad (6)$$

and the bias can be determined from Eq. (3). It may be noted that the bias can also be determined directly from modes 1 and 2 by the equation

$$B = \left[\frac{4\bar{A}_1 - \bar{A}_2}{\bar{A}_2 - \bar{A}_1} \right] R\omega^2 \quad (7)$$

however, this is inherently less accurate than Eq. (3) because it depends on small differences of large numbers.

In the true situation, the drag is not constant and the simplified expressions shown above do not apply. However, corresponding (but more complex) expressions can be developed if the acceleration due to drag can be approximated by a polynomial with unknown coefficients. It was found that a second degree polynomial spanning 400-sec data intervals provided an excellent fit and appropriate expressions were developed for such a model. The general form of the output for the case of variable drag is shown in Fig. 3.

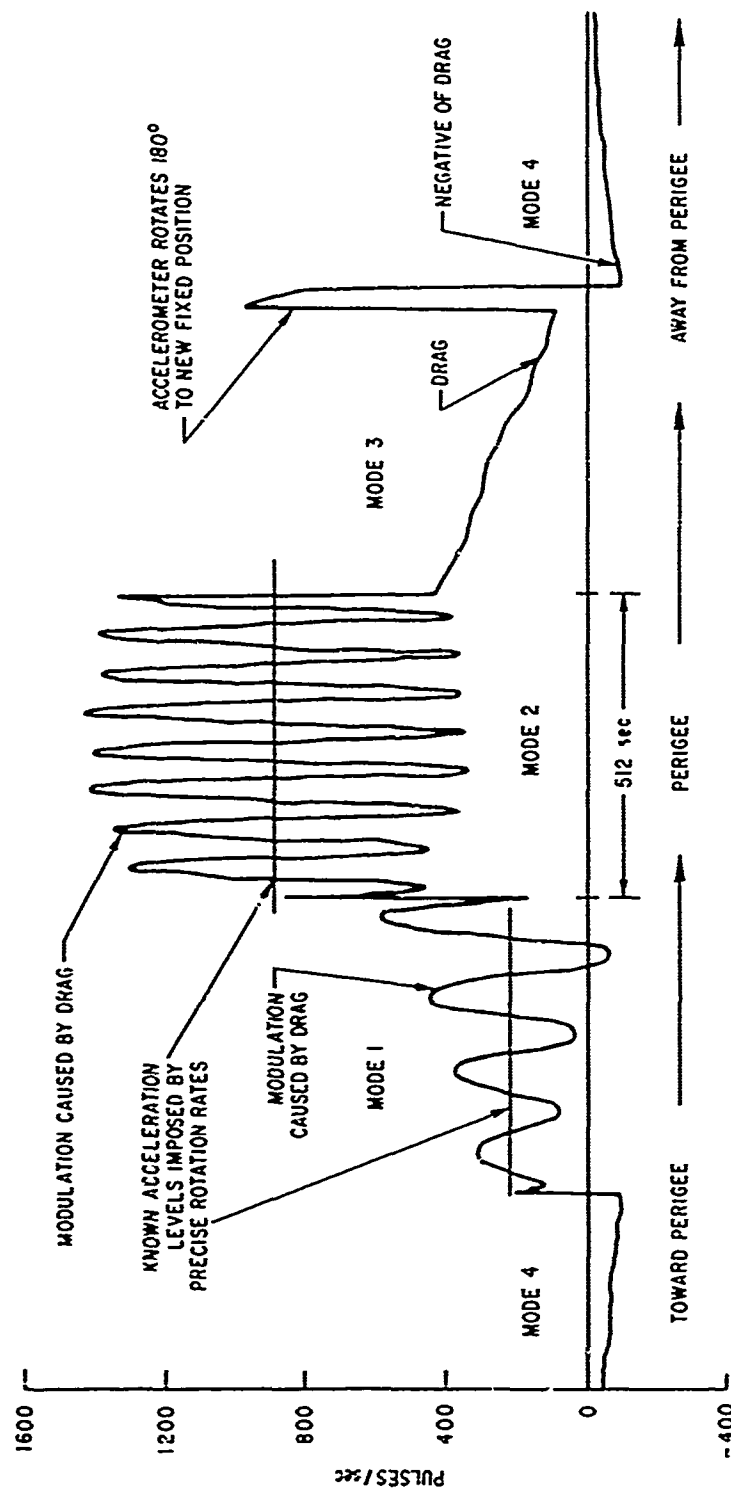


Figure 3. Characteristic Accelerometer Output (Realistic Case)

SECTION II

THE EQUIPMENT

The accelerometer used was developed by Bell Aerosystems Company and is known as the MESA (Miniature Electro-Static Accelerometer). The MESA was first flight-tested in July 1966 aboard an orbiting Saturn S-IVB stage. The results were reported in NASA TM X-1488, "Flight Test Evaluation of an Electrostatic Accelerometer for Measurement of Low-Level Orbital Acceleration," by D. J. Lesco, January 1968. It is interesting to note that the author of that document states:

"For the accurate measurement of low-level orbital accelerations of 10^{-4} g and lower, an extremely sensitive accelerometer with a low null bias (output at conditions of zero input) is required. A conventional accelerometer cannot be used because the null bias would be of the same order of magnitude as the accelerations to be measured. This bias results from the coupling into the accelerometer sensitive axis of the mechanical cross-axis forces required to support the acceleration sensing element (the accelerometer proof mass).

"An accelerometer designed to eliminate the null bias problem is the miniature electrostatic accelerometer MESA. The advantage of an electrostatically suspended accelerometer is the capability to reduce the cross-axis suspension forces for operation in a low-acceleration environment simply by reducing suspension voltages. The major disadvantage is the inability to calibrate the accelerometer in the environment in which it will operate."

The MESA consists of an electrostatically supported proof mass which is electrostatically pulse rebalanced along a preferred or sensitive axis. Figure 4 shows the complete MESA while Fig. 5 shows the instrument without the insulating cover. An exploded view of the MESA is shown in Fig. 6 and a cross section is shown in Fig. 7. The MESA proof mass is supported by eight electrodes which in pairs react with the proof mass to form a passive

resonant electrostatic suspension system. Motion of the proof mass along its sensitive axis due to an acceleration of the instrument is detected by a capacitance bridge. The bridge output triggers controlled voltage pulses to electrostatic forcer rings which oppose that motion. The output pulse rate is then directly proportional to the force on the proof mass and hence to the acceleration sensed by the instrument along its sensitive axis. In the actual flight application, a nominal full scale range of 5×10^{-4} g was selected for the MESA, corresponding to an output of 5000 pulses/sec. A more complete description of the MESA is presented in Appendix B.

The centrifuge assembly is shown in Fig. 8. The rotating member housed the MESA and the MESA electronics. The large "bull gear" shown in Fig. 8 was part of the rotating member. The power to drive the rotating member was provided by a hysteresis synchronous motor. The motor was a 400-Hz machine, but it was driven at 300 Hz and 600 Hz to provide the two speeds of mode 1 and mode 2. The power and signal leads from the frame of the centrifuge assembly to the rotating member were conveyed via a slip ring assembly mounted adjacent to the bull gear. The brush block of the slip ring assembly can be seen in Fig. 8. The position pickoffs indicated when the rotating member was positioned such that the MESA sensitive axis was fore or aft. These were simply reed relays actuated by a small magnet inset into the periphery of the rotating member. The reed relays can be seen fastened to the framework of the centrifuge in Fig. 8. The problem of lubrication for the slip rings while in the orbital environment was avoided by maintaining a partial atmosphere of dry air in the centrifuge assembly. The cover which enclosed the basic centrifuge shown in Fig. 8 contained a relief valve which maintained 4 psi gauge pressure. The seal between the cover and the baseplate of the centrifuge was effected with the gasket shown in Fig. 8.

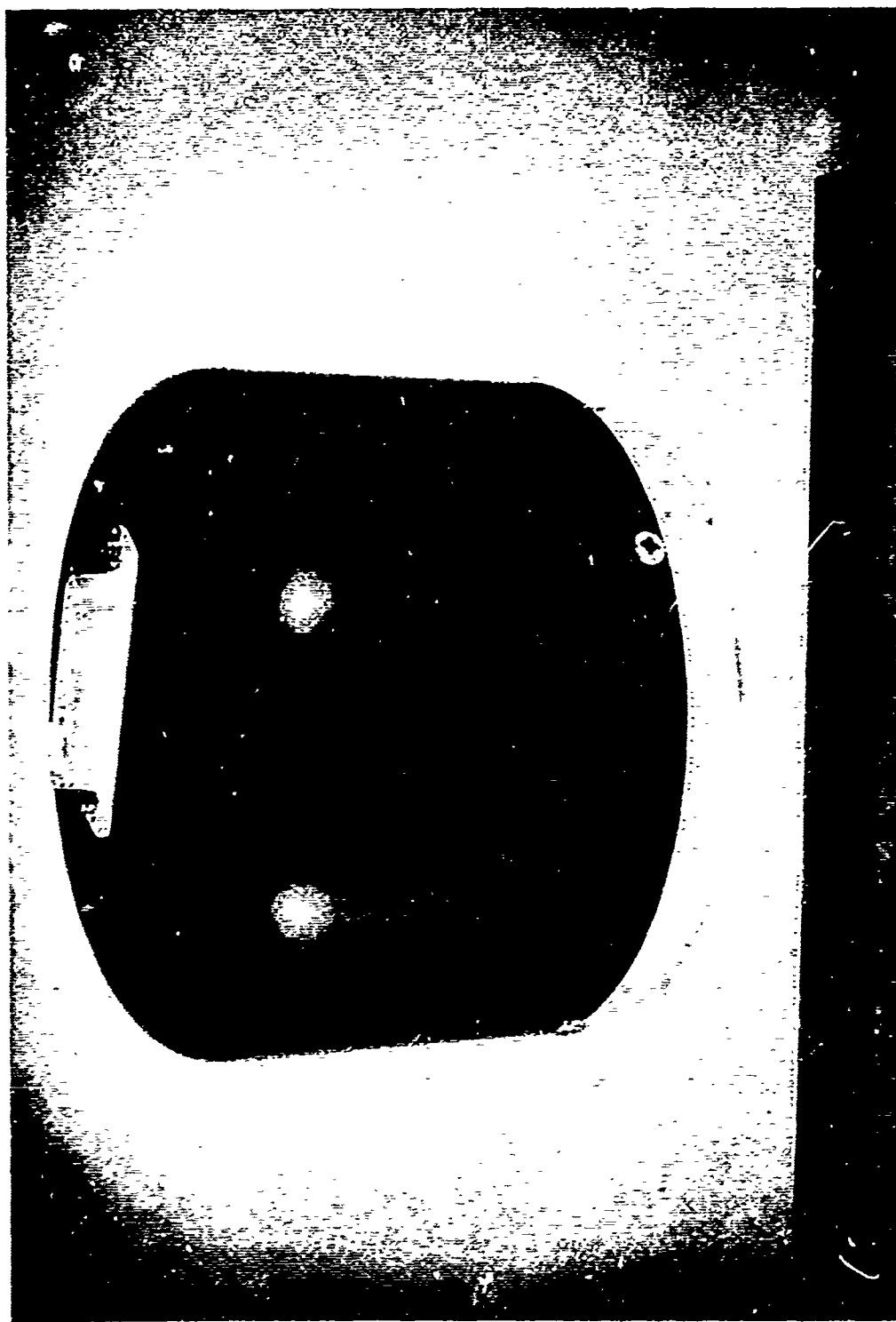


Figure 4. Exterior View of MESA Accelerometer

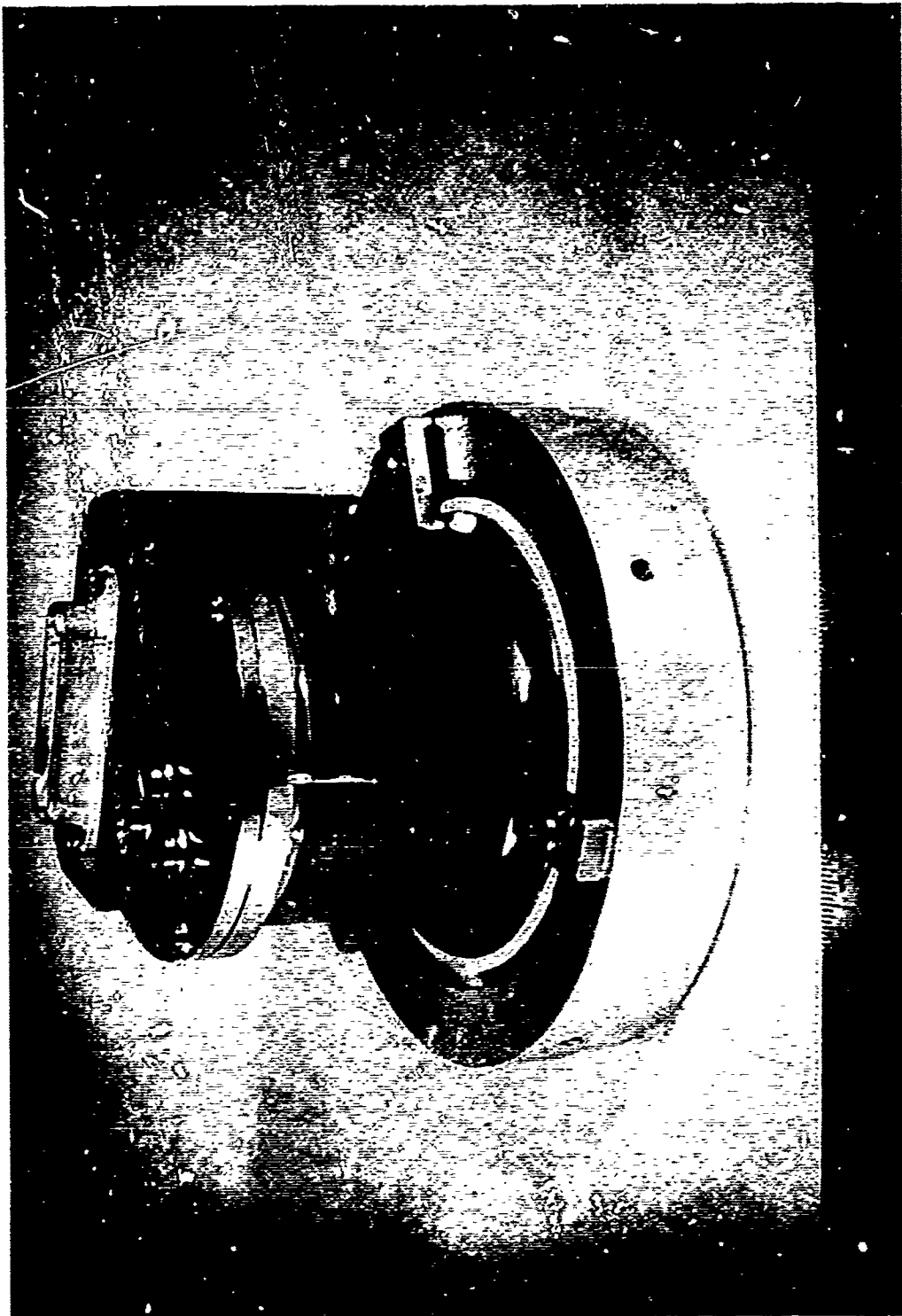


Figure 5. MESA Without Insulating Cover

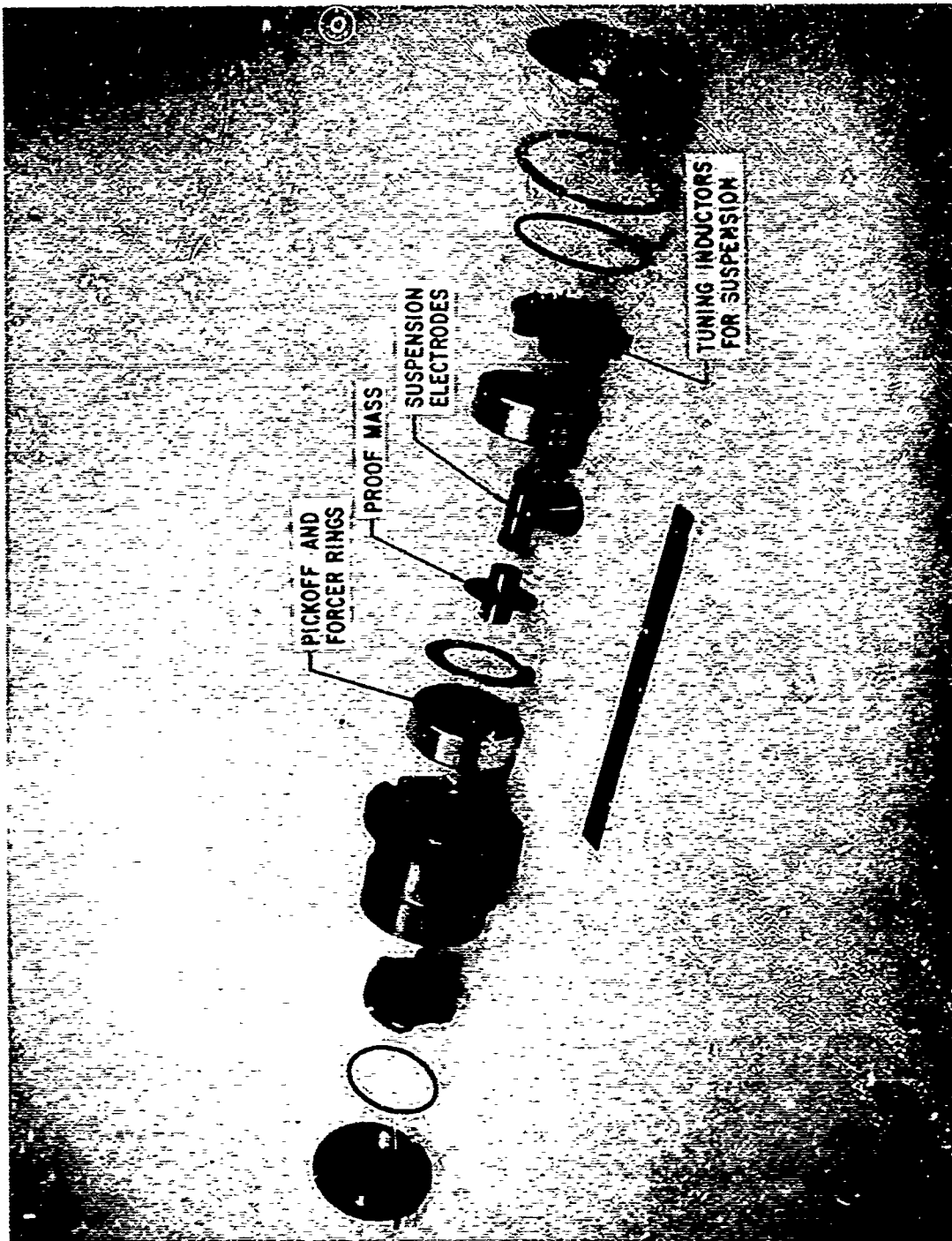


Figure 6. Exploded View of MESA

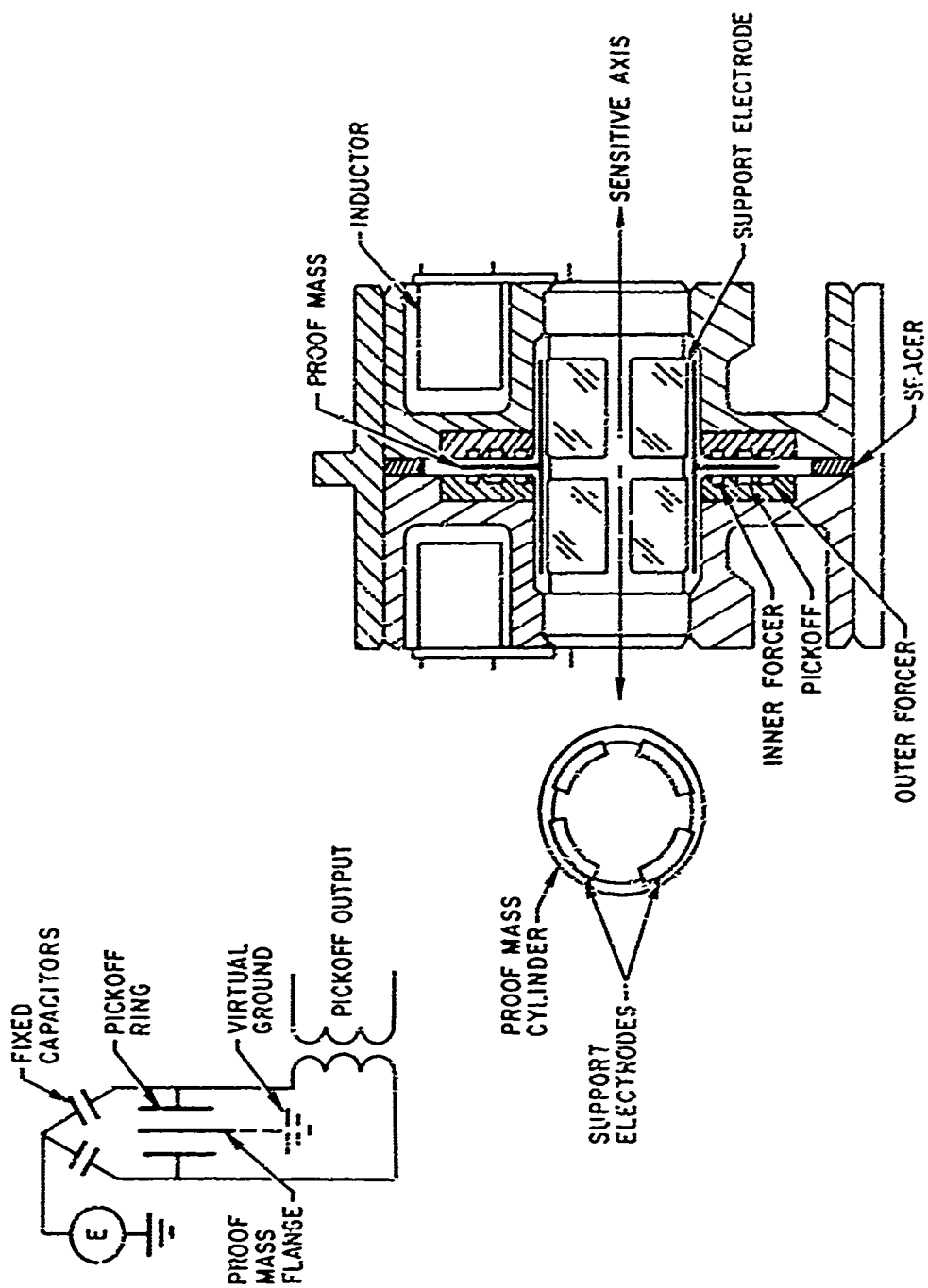


Figure 7, Cross Section of MESA

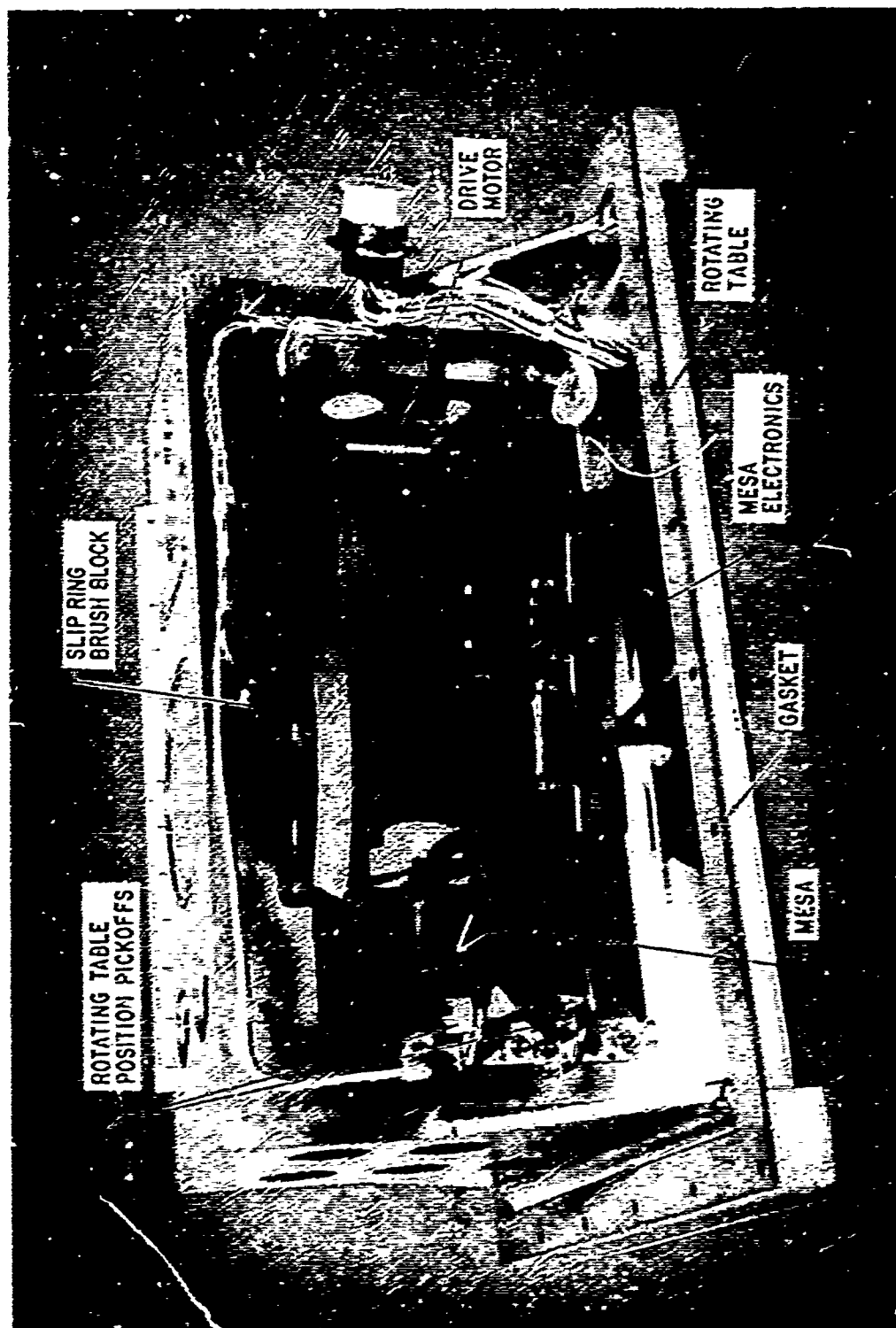


Figure 8. LOGACS Centrifuge

The LOGACS equipment included telemetry transmitters and attendant antennas as well as an S-band transponder for accurate tracking of the vehicle. In addition, a complete command receiving system was provided so that commands could be issued by the ground stations for purposes of controlling the equipment while on-orbit. An essential element, of course, was the data recorder. In addition to the primary information of accelerometer output, the LOGACS experiment provided the following:

- a. Experiment clock time in seconds since turn-on
- b. Mode status
- c. Two centrifuge table position pickoff monitors
- d. Agena attitude control jet monitors
- e. Agena gyro output signals
- f. Agena horizon scanner output signals
- g. MESA instrument temperature
- h. MESA electronics temperature
- i. Unregulated voltage monitor (28-volt).

SECTION IV

THE SPACECRAFT

The carrier vehicle was the Agena spacecraft built by Lockheed Missiles and Space Company (which also performed the integration function for the LOGACS experiment). The Agena vehicle is approximately 20 ft long and 5 ft in diameter. The LOGACS experiment was located, as shown in Fig. 9, about 10 ft aft of the Agena's center of gravity and about 2 ft below the center line. This offset position was considered in the data analysis. The Agena was attitude controlled during the experiment so that the plane of the turntable was maintained in the plane of the local horizontal and the axis of the Agena was held to within 2 deg of the direction of motion. Attitude control jet firings occurred throughout the flight and were clearly evident in the data. Knowledge of such events was employed in the data processing.

The entire LOGACS equipment array including telemetry and S-band transponder was accommodated on a bottom panel and a right side panel of the Agena aft equipment rack (see Fig. 10). The side panel is shown in Fig. 11, while the bottom panel is shown in Fig. 12. The antennas are not yet installed on the bottom panel shown in Fig. 12.

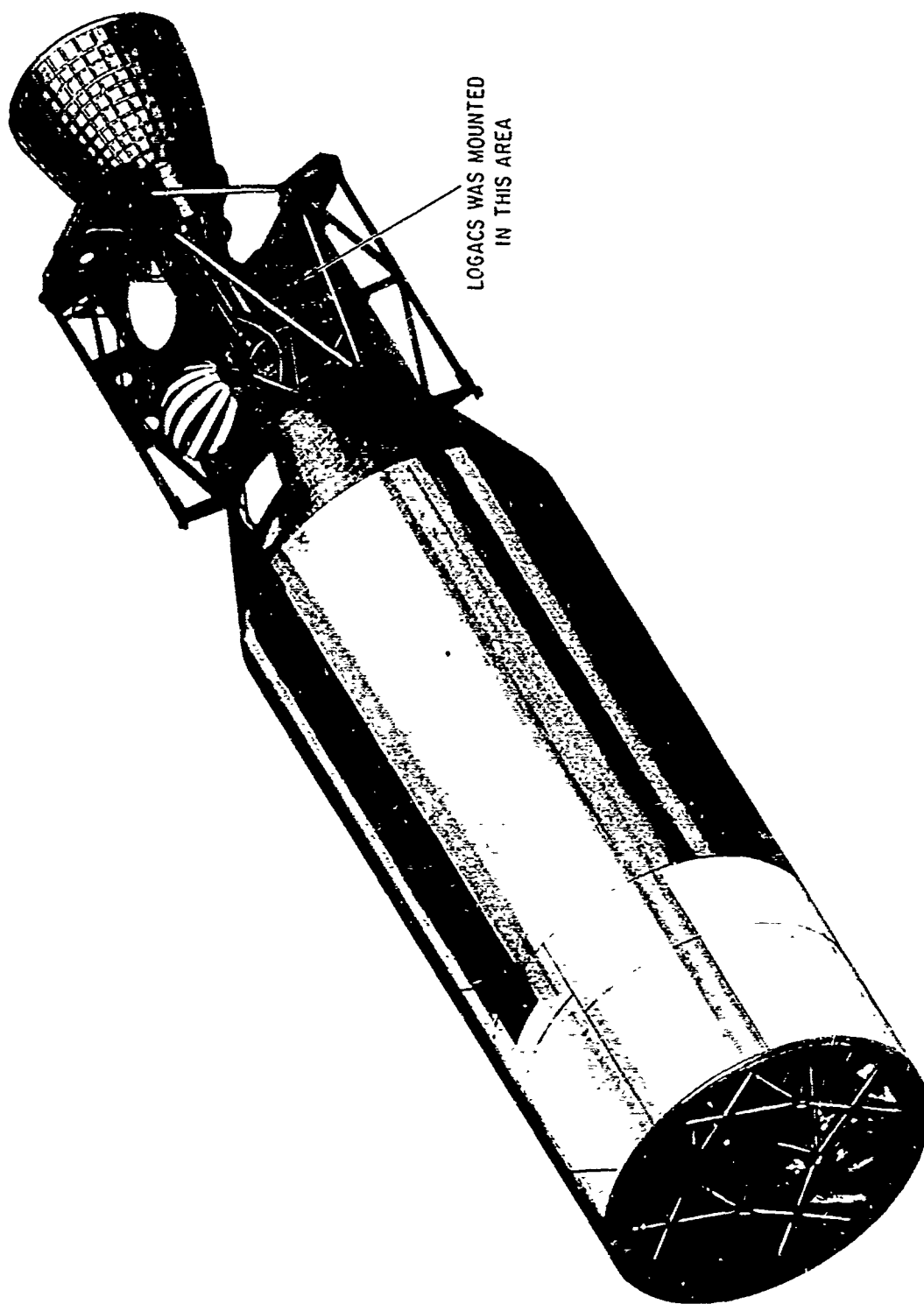


Figure 9. General Location of LOGACS Experiment on Agena Spacecraft

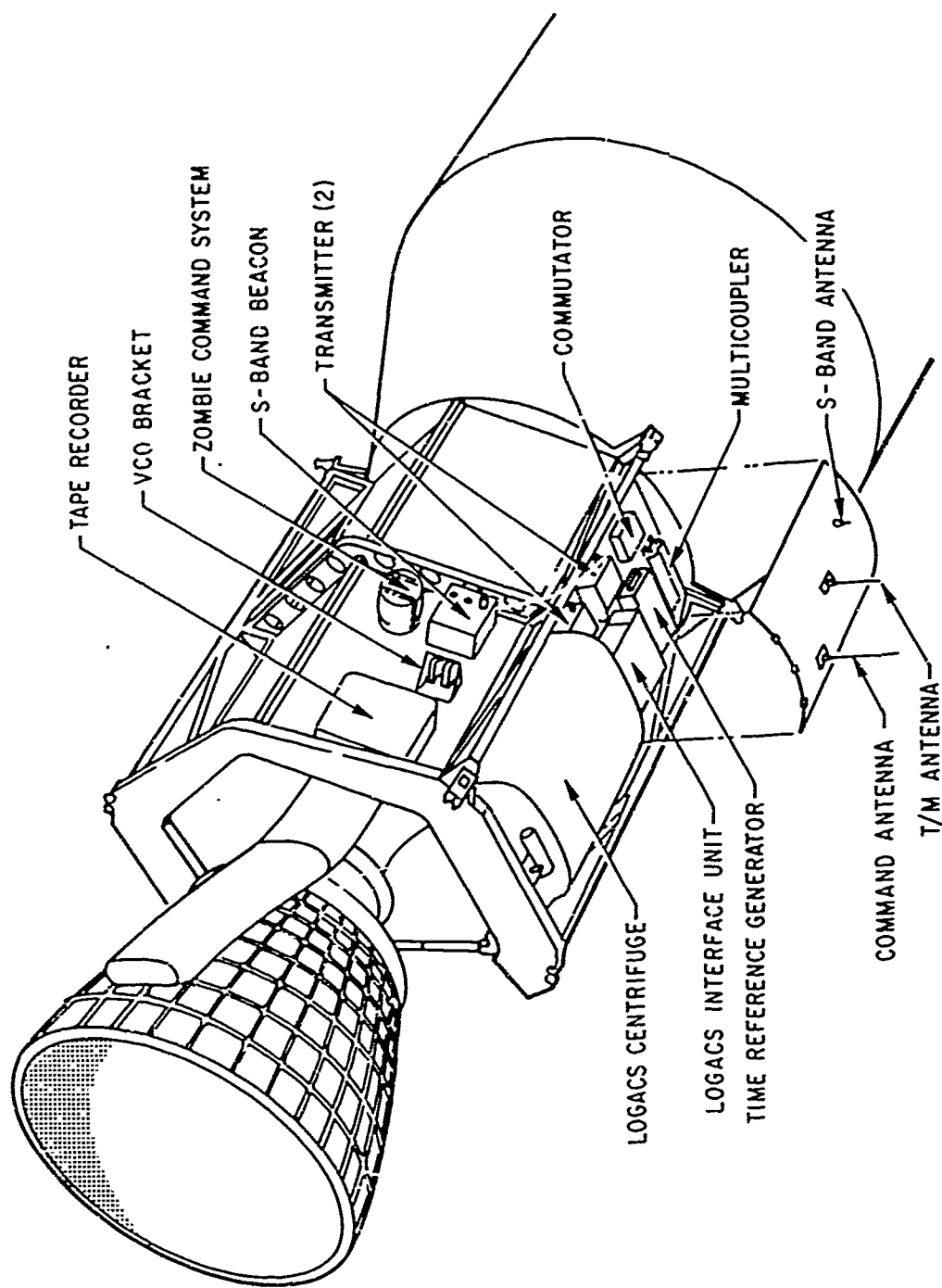


Figure 10. Specific Location of LOGACS Equipment

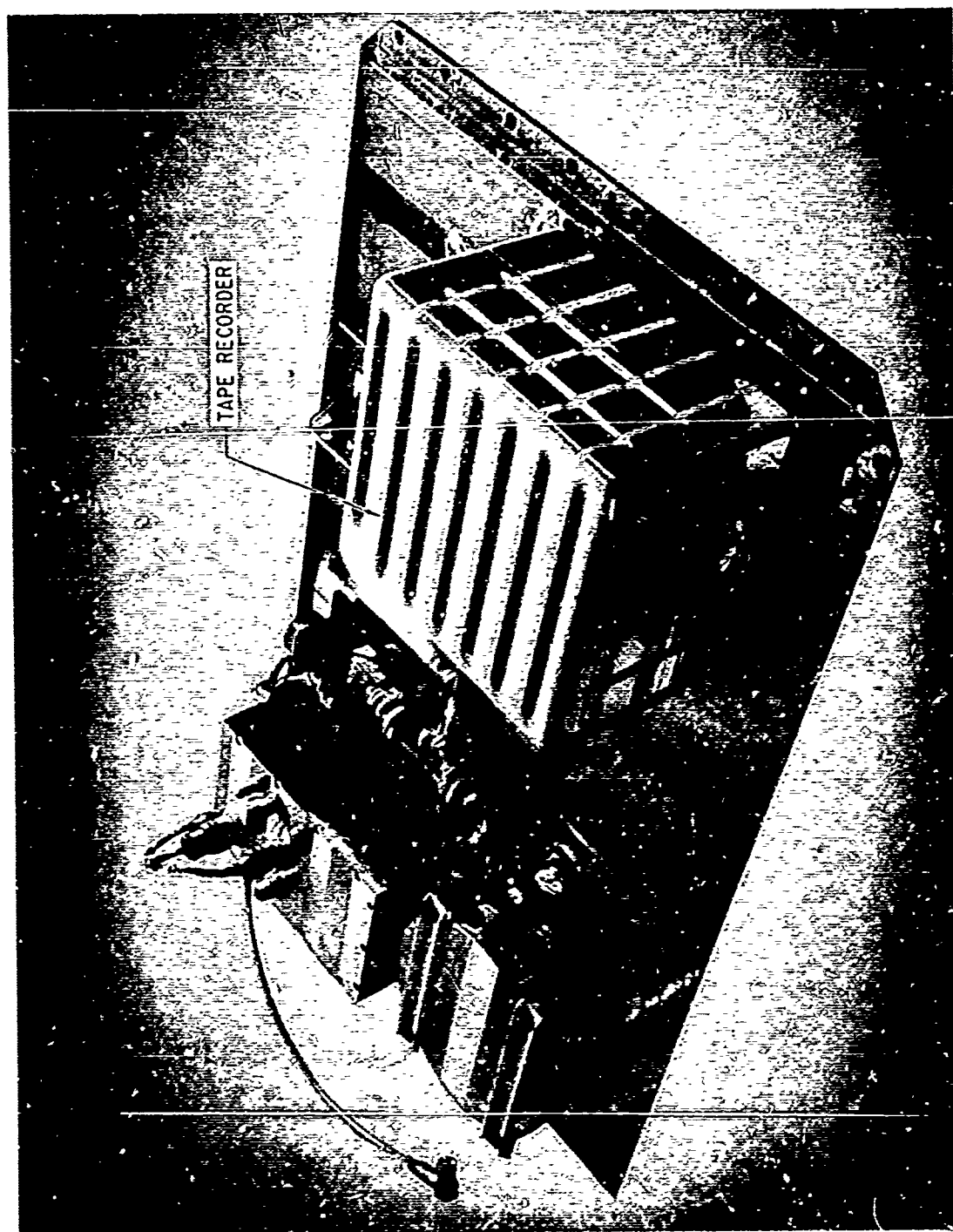


Figure 11. LOGACS Side Panel

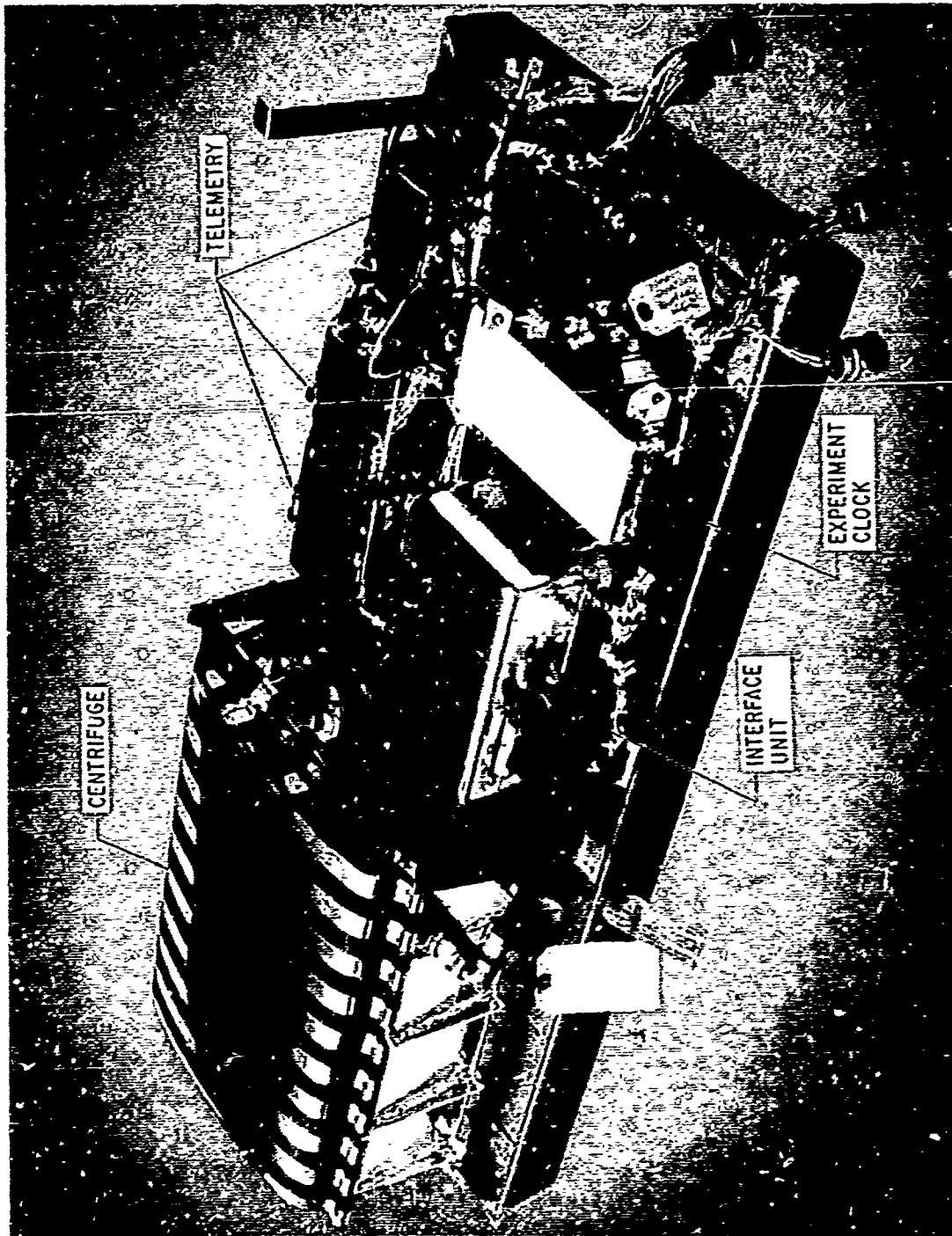


Figure 12. LOGACS Bottom Panel

SECTION V

THE FLIGHT

The LOGACS experiment was carried into orbit by an Atlas-Agena launched from the Western Test Range on 22 May 1967. The Agena carrier was given the satellite designation 1967 50B. The initial orbit elements are shown in Table 2. During the 18th revolution, apogee was raised to extend the lifetime by firing two solid propellant rockets. The subsequent orbit is also shown in Table 2.

Table 2. LOGACS Orbital Elements

	<u>Injection</u>	<u>Orbit Adjust</u>
Date	22 May 1967	23 May 1967
Time	1839 GMT	2124 GMT
Perigee	80 n mi	79.4 n mi
Apogee	193 n mi	217.8 n mi
Inclination	91.5 deg	91.5 deg
Eccentricity	0.015	0.018
Period	89.4 min	89.8 min
Argument of Perigee	136.7 deg	139.3 deg
Longitude of Node	217 deg	217 deg

At the first station acquisition after injection, it was found that all the LOGACS equipment seemed to be operating properly, but the MESA was saturated; that is, a full scale output was present constantly. This persisted for approximately three additional revolutions after which the readings were on scale. A similar behavior was noted subsequent to the orbit adjust firing on revolution 18. It had not been anticipated that the instrument would remain

saturated for such a long period after experiencing high accelerations. It is believed that this was due to the reduced effective force level acting to restore the proof mass when it departs from a near-central condition to an extreme displacement. This available restoring force level is only slightly in excess of the centripetal acceleration due to the centrifuge, which tends to maintain the proof mass at its extreme displacement. After the proof mass returned to its normal operating position, the instrument functioned properly.

A remarkably fortuitous event occurred during the flight in the form of an enormous solar disturbance. Geomagnetic activity was fairly low for the first 40 revolutions, but at about revolution 42 a great geomagnetic storm began. Near the end of May 25, the planetary range index K_p reached its maximum value of 9 for two successive 3-hour reporting periods -- an event which occurred only once before in the last 30 years. The great storm was accompanied by auroral activity as far south as New Mexico. The 10.7-cm solar flux also increased rapidly during this period and solar protons were detected with intensities up to six times normal. On May 24 at 1335 GMT, an extremely intense proton shower nearly 20 times higher than the normal level was recorded, but by 1600 GMT the protons began to fall off and within 1/2 hr had reduced by a factor of five from the peak level.

SECTION VI

RESULTS

The experiment succeeded in gathering over 100 hr of very accurate deceleration data which resulted in the following general conclusions:

- a. It was demonstrated that the plan for on-orbit calibration was in fact feasible.
- b. It was found that such calibration was necessary for precision measurements, since the resultant bias and scale factor differed significantly from the best estimates and computed extrapolations based on careful ground tests.
- c. The accelerometer parameter values deduced were consistent and stable throughout the flight.

A major by-product of the LOGACS calibration experiment was the acquisition of valuable information on atmospheric density variation and in particular the effect on density of the immense solar storm. The ability to infer density from the deceleration data was limited by the uncertainty associated with the effective ballistic coefficient $W/C_D A$ of the carrier vehicle and not by the accuracy of the accelerometer data. However, the variations or changes of density could be quite precisely determined and the LOGACS data constituted a significant addition to the available information concerning atmospheric characteristics at satellite altitude. The storm which occurred during the flight provided an opportunity to observe in great detail the response of the atmosphere to severe disturbance. The details of this aspect of the LOGACS flight results are not available for presentation at this time.

APPENDIX A

RELATED SATELLITE EXPERIMENTS

There are many techniques available to infer atmospheric density at satellite altitudes. The most common method depends on inferring drag from the observed change in period based on ground tracking data. This has the advantage that no special on-board equipment is required but suffers from the defect that only an integrated effect is available. Thus, the detailed drag structure is not revealed. The three satellite experiments described below have in common with LOGACS the feature that direct measurements are made of deceleration due to drag.

San Marco*

San Marco I, launched on 15 December 1964, represented the first successful satellite experiment to measure drag deceleration directly. It was launched from Wallops Island by an Italian team using a NASA Scout booster to inject the satellite into an initial orbit with a perigee of 205 km and an apogee of 821 km, resulting in a period of about 95 min. The satellite consisted of a clean-surfaced sphere of 26 in. diameter weighing 252 lb. The sensing technique consisted of measuring the displacement of the outer spherical shell relative to an internal frame. These were connected by a mechanical balance which permitted relative translation in any direction. The instrumentation was designed to provide data in the range from 200 to 300 km, and several minutes of useful information were obtained from almost every pass. On 26 April 1967, a similar satellite, San Marco II, was launched with a Scout booster from an equatorial ocean platform. The resulting orbit had a

*The information concerning San Marco I is based on the report by Professor Luigi Broglio, "Air Density Between 200 and 300 Km Obtained from San Marco I Satellite," presented to the Seventh International Space Science Symposium, Vienna, May 1966.

perigee of approximately 200 km and was almost equatorial (inclination less than 3 deg).

SPADES (Air Force Designation OV1-15)

In addition to an accelerometer to measure deceleration directly and a C-band beacon for tracking, the OV1-15 payload includes a microphone density gauge, ion gauges, mass spectrometers, energetic particle detectors, ionosphere monitor, and solar x-ray and ultraviolet flux monitors. The OV1-15 is intended to gather comprehensive diagnostic information on temperature, atmospheric composition, and external energy sources, together with density and deceleration measurements with the object of identifying the causes of atmospheric density fluctuations.

The spacecraft weighs about 400 lb and is intended to spin at 10 rpm. Information is recorded on a 2-hr tape recorder and power is provided by solar cells and batteries. Data are normally taken over the altitude range from 70 to 270 n mi. The accelerometers are a three-axis configuration of MESA accelerometers scaled to measure deceleration in the range of 10^{-5} to 10^{-10} g. The principal characteristics are as follows:

Booster:	Atlas
Launch Date:	June 1968
Launch Site:	Vandenberg Air Force Base
Attitude:	Spin stabilized - 10 rpm Spin axis - normal to orbit plane
Duty Cycle:	Instruments active below 270 n mi on alternate orbit only Data taken over full orbit several times each month
Orbit:	Initial Perigee - 85 n mi Initial Apogee - 1150 n mi Inclination - Polar Lifetime - 3 months Local Time - Noon-midnight initially; Dawn-dusk after 3 months

Cannonball (Air Force Designation OV1-16)

This is a high density satellite ($W/C_D A \approx 150 \text{ lb/ft}^2$) scheduled for launch about June 1968. Both a three-axis set of MESA accelerometers and a C band tracking beacon are to be carried to infer deceleration, but no diagnostic measurements of related phenomena are scheduled. The vehicle is unoriented and the tip-off rates will result in centrifugal forces induced by the angular motion. It is intended that these will be removed from the data by computation techniques. The orbit is to be polar with an initial perigee and apogee of 85 and 325 n mi, respectively. This will result in a lifetime of about 50 days. Since no tape recorder is carried, only real time data can be transmitted at favorable times. This is estimated to be about 40 min per day.

APPENDIX B

MESA ACCELEROMETER DESCRIPTION

The MESA proof mass is a hollow cylinder with a centrally located flange supported by eight electrodes each of which is in series with a tuning inductor. The capacitance in each tuned circuit changes as a function of the relative displacement of the proof mass from the support electrode. Since each resonant circuit is tuned to operate on the high frequency side of the resonance curve, each electrode-to-proof-mass voltage varies directly as the electrode-to-proof-mass displacement. As a result, the attractive force between each electrode and the proof mass increases as the electrode-to-proof-mass distance increases. This cross-axis support system for the proof mass constrains the proof mass translationally along the two axes perpendicular to the sensitive axis and rotationally about the same two axes. The proof mass remains rotationally unconstrained about the sensitive axis. The remaining degree of freedom of the proof mass is translation along the sensitive axis. Motion in this direction is restored by a pulse rebalance system.

The displacement of the proof mass along the sensitive axis is detected by an extremely sensitive capacitance bridge which, in simple form, is illustrated in the upper left corner of Fig. 7 (see Section III). The flange of the proof mass serves as the moving plate of the capacitance bridge while the pickoff ring in each housing is the fixed plate. Each pickoff-ring-to-flange capacitance forms a leg of the bridge while the other two legs can be assumed fixed and equal.

Displacement of the proof mass causes unbalance in the bridge, and its output, when amplified and phase-sensitive demodulated, provides a signal whose amplitude is proportional to displacement from center and whose polarity indicates sense.

When the demodulated output of the capacitance bridge reaches a fixed trigger level, the logic within the instrument gates a precisely controlled pulse from the pulse generator to the forcer rings. A pulse always goes to a pair (inner and outer) of forcer rings in one housing or the other. The logic which directs the pulse to one forcer ring pair or the other is set by the polarity of the demodulated bridge output.

When a pulse is directed to a forcer ring pair, the pulse polarity is such that a plus pulse is sent to one ring and a negative (i. e., inverted) pulse is sent to the other ring. Since the force on the proof mass is proportional to the square of the pulse voltage, the force resulting from the positive and negative pulses will be the same for equal area rings. More importantly, the artifice of using opposite polarities for the pulse on each forcer ring minimizes the buildup of charge on the proof mass.

The rate at which pulses are demanded is directly proportional to the net force on the proof mass and hence to acceleration applied along the sensitive axis.

Unclassified

Security Classification

DOCUMENT CONTROL DATA - R&D		
<small>(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified.)</small>		
1 ORIGINATING ACTIVITY (Corporate author) Aerospace Corporation El Segundo, California		2a REPORT SECURITY CLASSIFICATION Unclassified 2b GROUP
3 REPORT TITLE Precision Measurement of Satellite Acceleration: The LOGACS Experiment		
4 DESCRIPTIVE NOTES (Type of report and inclusive dates)		
5 AUTHOR(S) (Last name, first name, initial) Adams, B. L. ; Fotou, E. G. ; and Levin, E.		
6 REPORT DATE 68 JUL 15	7a TOTAL NO OF PAGES 33	7b NO OF REFS None
8a CONTRACT OR GRANT NO F04701-68-C-0200 b PROJECT NO c d	9a ORIGINATOR'S REPORT NUMBER(S) TR-0200(4306-02)-5 9b OTHER REPORT NO(S) (Any other numbers that may be assigned this report) SAMSO TR 69-6	
10 AVAILABILITY/LIMITATION NOTICES This document is subject to special export controls and each transmittal to foreign governments or foreign nationals may be made only with prior (Continued)		
11 SUPPLEMENTARY NOTES	12 SPONSORING MILITARY ACTIVITY Space and Missile Systems Organization Air Force Systems Command Los Angeles, California	
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DD FORM 1473
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Security Classification

Low-G Accelerometer Calibration System
LOGACS Experiment
Precise Satellite Acceleration Measurement
On-Orbit Accelerometer Calibration
Miniature Electrostatic Accelerometer

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